

AFRL-IF-RS-TR-2001-221
Final Technical Report
October 2001



EXPLORING DISJUNCTIVE PLANNING AS A MEANS TO SCALE-UP PLAN SYNTHESIS

Arizona State University

Sponsored by
Defense Advanced Research Projects Agency
DARPA Order No. C677

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

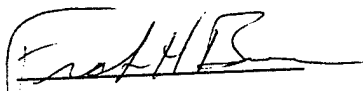
The views and conclusions contained in this document are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the U.S. Government.

AIR FORCE RESEARCH LABORATORY
INFORMATION DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

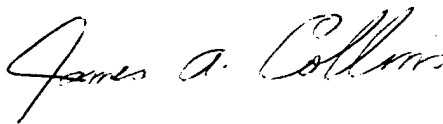
20020117 018

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-IF-RS-TR-2001-221 has been reviewed and is approved for publication.



APPROVED: FRANK H. BORN
Project Engineer



FOR THE DIRECTOR: JAMES A. COLLINS, Acting Chief
Information Technology Division
Information Directorate

If your address has changed or if you wish to be removed from the Air Force Research Laboratory Rome Research Site mailing list, or if the addressee is no longer employed by your organization, please notify AFRL/IFTB, 525 Brooks Rd, Rome, NY 13441-4505. This will assist us in maintaining a current mailing list.

Do not return copies of this report unless contractual obligations or notices on a specific document require that it be returned.

EXPLORING DISJUNCTIVE PLANNING AS A MEANS TO SCALE-UP PLAN
SYNTHESIS

Subbarao Kambhampati

Contractor: Arizona University
Contract Number: F30602-98-1-0182
Effective Date of Contract: 30 April 1998
Contract Expiration Date: 15 July 2000
Short Title of Work: Exploring Disjunctive Planning
Period of Work Covered: Apr 98 – Jul 00

Principal Investigator: Subbarao Kambhampati
Phone: (602) 965-0835
AFRL Project Engineer: Frank Born
Phone: (315) 330-4726

Approved for public release; distribution unlimited.

This research was supported by the Defense Advanced Research
Projects Agency of the Department of Defense and was monitored
by Frank Born, AFRL/IFTB, 525 Brooks Rd, Rome, NY, 13441-4505.

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503</small>				
1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE Oct 01	3. REPORT TYPE AND DATES COVERED Final Apr 98 - Jul 00		
4. TITLE AND SUBTITLE EXPLORING DISJUNCTIVE PLANNING AS A MEANS TO SCALE-UP PLAN SYNTHESES		5. FUNDING NUMBERS C - F30602-98-1-0182 PE - 62301E PR - C677 TA - 01 WU - P1		
6. AUTHOR(S) Sabbarao Kambhampati				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Arizona State University Dept of Computer Science and Engineering Tempe, AZ 85287-5406		8. PERFORMING ORGANIZATION REPORT NUMBER CRA5975-FT		
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Defense Advanced Research Projects Agency 3701 North Fairfax Drive Arlington, VA 22203-1714		10. SPONSORING/MONITORING AGENCY REPORT NUMBER AFRL-IF-RS-TR-2001-221		
11. SUPPLEMENTARY NOTES AFRL Project Engineer: Frank Born, IFTB, 315-330-4726				
12a. DISTRIBUTION AVAILABILITY STATEMENT Approved for public release; distribution unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) In this research, we have concentrated on exploring the advantages of disjunctive plan representations in improving planning performance. The results of the research included: 1) development of a system called GP-CSP, which uses direct constraint satisfaction techniques to solve the planning graph of Graphplan; 2) development of a method where the distance heuristics that were originally developed as part of the heuristic state search community can be applied to the backward search of Graphplan, a disjunctive planner; and 3) evaluation of the utility of different types of mutex propagation routines in the context of SAT and CSP encodings of the automated planning problems. The results of this research have been disseminated to the planning community through three publications in the 5th International Conference on Artificial Intelligence Planning Scheduling and one publication in the 2000 National Conference on Artificial Intelligence.				
14. SUBJECT TERMS Automated Planning, Disjunctive Planners, Constraint Propagation, Heuristics for Planning			15. NUMBER OF PAGES 16	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

Exploring Disjunctive Planning as a means to scale-up Plan Synthesis: Final Report on AFRL F20602-98-1-0182

1 Executive Summary

In this research, we have concentraed on exploiting the advantages of disjunctive plan representations in improving planning performance. The following are three of the important results of this research, all of which were published in the proceedings of the International Conference on AI Planning and Scheduling Systems:

- We developed a system called GP-CSP, which uses direct constraint satisfaction techniques to solve the planning graph of Graphplan. This system allowed us to closely study the impact of CSP representations and constraint propagation techniques, variable and value ordering techniques on the performance of the planner. This work has been presented at AIPS-2000, and has recently been submitted to Artificial Intelligence Journal. URLs for the GP-CSP system is: <http://rakaposhi.eas.asu.edu/gp-csp.html>
- We developed a method where by the distance heuristics that were originally developed as part of the heuristic state search community can be applied to the backward search of Graphplan, a disjunctive planner. Our work lead to a version of Graphplan that is significantly faster than the original Graphplan algorithm. A paper on this work was published in the proceedings of AIPS-2000.
- We also evaluated the utility of different types of mutex propagation routines in the context of SAT and CSP encodings of the automated planning problems. This work allowed us to settle the question as to the true impact of the mutex propagation routines on the SAT encodings. The results of this work have been published at AIPS-2000.

The research results summarized above have also lead us to some very significant follow-on efforts.

- The work on distance-based variable ordering techniques for Graphplan has eventually lead us to develop the AltAlt system, which cleverly complements the relative advantages of Graphplan and state-space search systems. AltAlt uses the Graphplan's Planning graph to derive very high quality heuristics that are used to focus the search of a backward state search planner. As such, AltAlt effectively integrates the ideas of conjunctive and disjunctive planners. Papers based on the AltAlt system have been presented at AAAI-2000 and KBCS-2000. A longer journal submission based on this work has recently been accepted to the Artificial Intelligence Journal. The URL for the AltAlt page is <http://rakaposhi.eas.asu.edu/altweb/altalt.html>
- The work on the CSP encodings for partial order planning has lead to the RealPlan system, which attempts to integrate planning and scheduling functions in a loosely integrated architecture. Specifically, since most approaches to scheduling are already based on CSP encodings, we were able to provide an effective integration using the GP-CSP system, which does planning using CSP. The resulting system, called RealPlan, has been shown to be able to scale up better than monolithic planners, in domains where one has both causal and resource reasoning components. This work has been published in AAAI-2000 and a longer paper on it has been accepted to the Artificial Intelligence Journal. The URL for the AltAlt page is at <http://rakaposhi.eas.asu.edu/realplan.html>

2 Abstracts of the relevant papers

This section lists the abstracts of the papers that directly resulted from the research supported by this grant.

Planning as Constraint Satisfaction: Solving the planning graph by compiling it into CSP

The idea of synthesizing bounded length plans by compiling planning problems into a combinatorial substrate, and solving the resulting encodings has become quite popular in recent years. Most work to-date has however concentrated on compilation to satisfiability (SAT) theories and integer linear programming (ILP). In this paper we will show that CSP is a better substrate for the compilation approach, compared to both SAT and ILP. We describe GP-CSP, a system that does planning by automatically converting Graphplan's planning graph into a CSP encoding and solving it using standard CSP solvers. Our comprehensive empirical evaluation of GP-CSP demonstrates that it is superior to both Blackbox system, which compiles planning graphs into SAT encodings, and ILP-based planner in a wide range of planning domains. Our results show that CSP encodings outperform SAT encodings in terms of both space and time requirements in various problems. The space reduction is particularly important as it makes GP-CSP less susceptible to the memory blow-up associated with SAT compilation methods. The paper also discusses various techniques in setting up the CSP encodings, planning specific improvements to CSP solvers, and strategies for

variable and value selection heuristics for solving the CSP encodings of different types of planning problems.

Distance-based Goal-ordering techniques for Graphplan

It has been observed in the literature that the backward search of Graphplan algorithm can be seen as solving a dynamic CSP problem. Given this relation, the order in which the backward search considers goals for expansion—the so-called “variable ordering heuristic”, and the order in which the actions supporting those goals are considered – i.e., the “value ordering heuristic”—can have a very significant impact on Graphplan’s performance. Despite this expectation, experiments with the traditional CSP variable ordering strategies such as “most constrained variable first” and “least constrained value first”—have been shown to be of at best marginal utility. In this paper, we propose a class of variable and value ordering strategies that are based a notion of the difficulty of achieving the corresponding subgoal. The difficulty of achievement is quantified by the first level of the planning-graph at which that subgoal appears. We will argue that these are better suited to the dynamic CSP problem addressed by Graphplan’s backward search. We backup our arguments by empirical studies that demonstrate that our heuristics lead to orders of magnitude improvement in Graphplan’s backward search. We will end with a discussion of the relations between this heuristic and the distance based heuristics used by UNPOP and HSP planners.

Investigating the Effect of Relevance and Reachability Constraints on SAT Encodings of Planning

Currently, Graphplan and Blackbox, which converts Graphplan’s plan graph into the satisfaction (SAT) problem, are two of the most successful planners. Since Graphplan gains its efficiency from the forward propagation of reachability based mutual exclusion constraints (mutex) and their backward use, it has been believed that SAT encoding will also benefit from mutexes. In this paper, we will try to answer two important questions: (1) Are mutual exclusions actually useful for solution extraction in SAT encoding? (2) Are there other useful constraints that can be propagated on the planning graph which may help SAT solvers? Our experiments with systematic solvers Relsat and Satz shows that though forward mutexes are useful in general, there are domains in which mutex constraints can slow down search. More over, we introduce the notion of backward mutex and their propagation which is based on relevance analysis and implement it in Blackbox. We find that the addition of relevance based backward mutual exclusions helps speedup the Relsat solver in solving the SAT encoding of many standard planning problems.

RealPlan: Loosely Coupled Architectures for Integrating Planning and Scheduling

In most real-world reasoning problems, planning and scheduling phases are loosely coupled. For example, in project planning, the user comes up with a task list and schedules it with a scheduling tool like Microsoft Project. One can view automated planning in a similar way in which there is an action selection phase where actions are selected and ordered to reach the desired goals, and a resource allocation phase where enough resources are assigned to ensure the successful execution of the chosen actions. On the other hand, most existing automated planners studied in Artificial Intelligence do not exploit this loose-coupling and perform both action selection and resource assignment employing the same algorithm. The current work shows that the above strategy severely curtails the scale-up potential of existing state of the art planners which can be overcome by leveraging the loose coupling.

Specifically, a novel planning framework called RealPlan is developed in which resource allocation is de-coupled from planning and is handled in a separate scheduling phase. The scheduling problem with discrete resources is represented as a Constraint Satisfaction Problem (CSP) problem, and the planner and scheduler interact either in a master-slave manner or in a peer-peer relationship. In the former, the scheduler simply tries to assign resources to the abstract causal plan passed to it by the planner and returns success. In the latter, a more sophisticated “multi-module dependency directed backtracking” approach is used where the failure explanation in the scheduler is translated back to the planner and serves as a *nogood* to direct planner search.

RealPlan not only preserves both the correctness as well as the quality (measured in length) of the plan but also improves efficiency. Moreover, the failure-driven learning of constraints can serve as an elegant and effective approach for integrating planning and scheduling systems. Beyond the context of planner efficiency, the current work can be viewed as an important step towards merging planning with real world problem solving where plan failure during execution can be resolved by undertaking only necessary resource re-allocation and not complete re-planning.

Publications that acknowledge this grant

1. Extracting effective and admissible heuristics from the planning graph. X. Nguyen and S. Kambhampati. AAAI 2000. (Acceptance ratio: 30)
2. M. Do and S. Kambhampati. Solving Planning Graph by Compiling it into a CSP. Proc. 5th AIPS. 2000. (Acceptance ratio: 30)
3. S. Kambhampati and R. Nigenda. Distance-based goal ordering heuristics for Graphplan. Proc. 5th AIPS 2000. (Poster. Acceptance ratio: 40)
4. M. Do, B. Srivastava and S. Kambhampati. Investigating the effect of Relevance and Reachability Constraints on SAT encodings of Planning. Proc. 5th AIPS 2000. (Poster. Acceptance ratio: 40)

***MISSION
OF
AFRL/INFORMATION DIRECTORATE (IF)***

*The advancement and application of Information Systems Science
and Technology to meet Air Force unique requirements for
Information Dominance and its transition to aerospace systems to
meet Air Force needs.*